INERTIAL CONFINEMENT FUSION AT LOS ALAMOS—
The Pursuit of Ignition and Science-Based Stockpile Stewardship

Cris W. Barnes, D. Baker, B. Bauer , J. B. Beck, R. Berggren, R. E. Chrien, M. Clover, J. Cobble, C. A. Coverdale[†], M. Cray, N. Delamater, D. DuBois, B. H. Failor[†], J. C. Fernández, L. Foreman, R. Gibson, P. Gobby, S. Goldman, D. Harris, A. Hauer, J. Hoffer, N. Hoffman, W. W. Hsing, R. Johnson, G. Kyrala, E. Lindman, G. Magelssen, R. Mason, D. Montgomery, T. J. Murphy, J. Oertel, D. P. Smitherman, F. Swenson, G. Pollak, H. Rose, K. Schoenberg, M. S. Sorem, D. Tubbs, W. Varnum, H. Vu, J. Wallace, R. Watt, B. Wilde, M. Wilke, D. Wilson, W. M. Wood

Los Alamos National Laboratory
MS-E526
Los Alamos, NM 87545
(505)665-5687

ABSTRACT

Los Alamos National Laboratory is contributing to the core science and technology of the inertial confinement fusion program leading to the National Ignition Facility. Short summaries of a sample of recent experimental and related theoretical work are presented.

I. INTRODUCTION

The Los Alamos Inertial Confinement Fusion (ICF) Program has two principal goals: 1) to perform research that is central to the achievement of ignition on the National Ignition Facility (NIF), and 2) to develop and utilize ICF techniques and methods in pursuit of science-based stockpile stewardship (SBSS) of core nuclear weapons research. These goals have driven a program that includes experiments on various high energy laser facilities, advanced theoretical modeling, and target fabrication materials research.

In this paper we describe examples of our current research that investigate issues that are crucial to these goals. The Los Alamos ICF program has five principal elements: (1) Hohlraum Plasma Dynamics seeks to improve the understanding of indirect drive necessary for ignition and the application of indirect drive for core weapons experiments; (2) Capsule Implosion Physics addresses hydrodynamics issues common to implosion physics for ignition and improving hydrodynamics predictive capability for the core weapons program; (3) Target Fabrication Technology develops technology required for building and fielding ignition targets as well as targets for ongoing experimental campaigns; (4) Computational Assessment improves prediction of ICF target behavior for ignition and advances computational capability needed for core weapons utilization of laser facilities; and (5) Target Experimental Technology includes development of methods and techniques essential in utilizing ICF facilities including diagnostic and instrument development, optical fabrication technology development, and the operation of the Trident laser facility. We present a sample of recent experimental and related theoretical work in hohlraum plasma dynamics and capsule implosion physics; describe work on NIF target design, target fabrication technology, and related new initiatives; and conclude with comments on weapons physics using large lasers.

II. HOHLRAUM PLASMA DYNAMICS

Two key issues for achieving ignition are the accurate measurement and control of radiation drive symmetry in hohlraums and the suppression of laser plasma instabilities that reduce drive efficiency and affect drive symmetry by unwanted light scattering. Central to these efforts is the development of advanced radiation-hydrodynamic theory and computation used to model the experiments.

In a vacuum hohlraum, as the “spots” from the individual laser beams hit and interact with the inner wall of the hohlraum, the high-Z material is heated and hydrodynamically moves to fill the hohlraum. This moving high-Z plasma changes where the laser deposits its energy and generates x rays (and hence changes the symmetry of the x-ray drive). Simulations of the hohlraum motion in vacuum hohlraums have successfully predicted the drive symmetry.[1] The moving plasma also causes stagnation of plasma flow on the hohlraum axis that affects the drive. Low-Z liner material was tried to constrain this spot motion and control the time-dependent symmetry of the x-ray drive; it worked, but is still predicted to cause stagnation on axis in NIF hohlraums. Gas-fills in the hohlraum are now used successfully to tamp the wall motion and eliminate axial stagnation. However, there is a continuing discrepancy between data and calculations for the spot motion (and hence symmetry) for gas-filled hohlraums.[2]

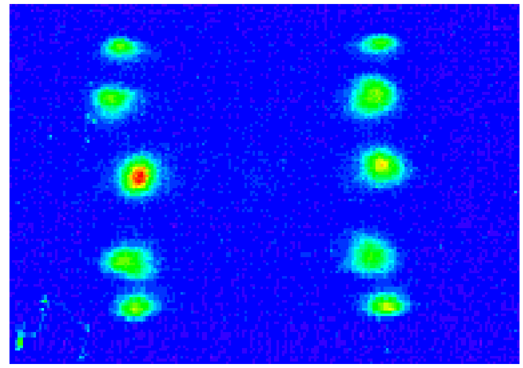
A. Development of Thinwall Hohlraums

Typical scale 1 hohlraums used on the Nova laser facility have 25 micron thick gold walls. Such thick walls are opaque to the x-ray emission of imploding capsules, thus requiring diagnostic holes in them. They also block all but the hardest (>20 keV) of x rays from the laser beam interaction spots.

Thin wall hohlraums made of only 2 microns gold coated onto plastic have the advantage of allowing x rays greater than ~5 keV to be seen through the hohlraum wall. This allows direct imaging of the x-ray emission produced by the laser beam interaction on the wall of the hohlraum. Such thinwall hohlraums were developed in the early days of the ICF program, and have been increasingly used to measure the hydrodynamic spot motion and beam deflection in gas-filled hohlraums. Figure 1 illustrates data from a typical thinwall hohlraum shot on Nova.

B. Beam Deflection Experiments on Trident

With the discovery that the laser-beam spots in gas-filled hohlraums did not occur in the same locations as in vacuum hohlraums, a search began for an explanation of what could move the laser beam. It was recognized that “hot spots” or regions of high intensity in the laser beam could dig density wells by the ponderomotive force. The resulting density gradients changed the index of refraction for the beam propagation. It was then hypothesized that hydrodynamic plasma flow in the hohlraum could move the density wells and deflect the laser beam in the direction of flow[3] (see Figure 2).



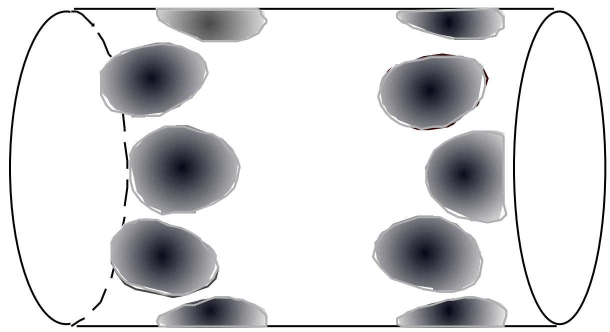


Figure 1: Example of x-ray image from thinwall hohlraum on Nova. The view is not orthogonal to the hohlraum axis, so the individual laser beam spots appear offset. Below it is drawn the outline of the hohlraum and the laser intensity contours. Hohlraums like these will be used for indirect-drive studies at OMEGA-Upgrade.

This hypothesis was tested in experiments on the Trident laser facility where, by bouncing a chirped-frequency laser off a grating, the laser beam was swept relative to a plasma (rather than the plasma flowing past the laser beam). Confirmation that beam deflection could be caused by the interaction of laser hot-spots and plasma flow was made.

C. Control of Laser Scattering due to Plasma Instabilities in Hohlraums

Laser-plasma instability experiments are crucial for both successful ignition demonstration and for developing NIF to accommodate high-temperature weapons physics experiments. Los Alamos has led efforts to design and characterize gas-filled Nova hohlraums with plasma conditions and scale lengths approaching conditions expected in ignition hohlraums. By changing the gas fill either the plasma conditions (electron density or temperature) or the damping of ion

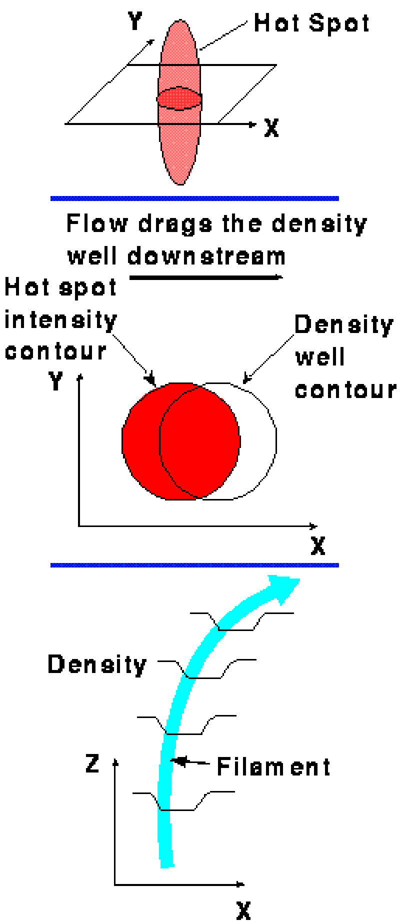


Figure 2: Explanation of how laser-beam hot spots create a density well through the ponderomotive force which via plasma flow causes the beam to deflect in the direction of flow.

acoustic waves can be varied. Clear evidence of an onset intensity above which Stimulated Brillioun Scattering (SBS) saturates is seen.[4,5] While the onset intensity is theoretically understood,[6] the observed SBS saturation levels are much lower than linear and non-linear theoretical predictions. Both the SBS and Stimulated Raman Scattering (SRS) reflectivities depend on the level of acoustic-wave damping. Measured SBS levels generally decrease as damping increases. On the other hand, measured SRS reflectivities increase with increased acoustic damping[7] (see Figure 3). This is consistent with SRS levels being controlled by Langmuir turbulence, which arises via the parametric decay instability.

We are just completing the fabrication and will be soon installing a Full Aperture Backscatter Station (FABS) on Nova which includes the

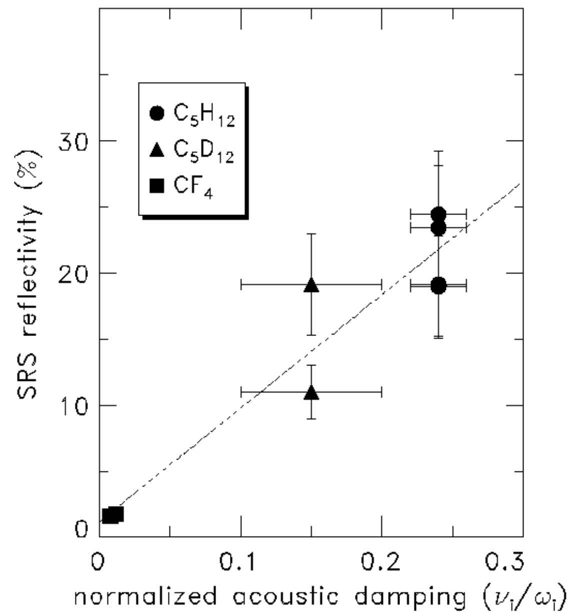


Figure 3: Stimulated Raman Scattering (SRS) reflectivity measured in gas-filled toroidal hohlraums in three different gases to vary the acoustic damping rate.

capability of imaging backscattered light from targets. The imaging FABS-2 diagnostic will provide spatial resolution of the sources of plasma instability in the hohlraum. It will have 25 μm spatial resolution over the visible wavelength region of 350–700 nm. This advanced diagnostic should allow characterization of mutual SRS and SBS competition and seeding with imaging of NIF-like toroidal hohlraums.

III. CAPSULE IMPLOSION PHYSICS

Another key issue of the ICF program is investigation of hydrodynamic instabilities that limit ignition target design. Three experimental campaigns are described here: convergent ablative Rayleigh-Taylor instabilities in two-dimensional, cylindrical geometry; measuring “mix” from deuterated-plastic shell implosions; and mitigation of laser beam nonuniformity and imprinting by foam “buffering” in direct drive.

A. Ablative Rayleigh-Taylor Instabilities in a Convergent Geometry (Cylinders)

Much excellent work has been done on quantifying comparisons of ablative Rayleigh-Taylor instabilities with theoretical and computational models in planar geometries.[8] Primary interest, of course, is in study of these instabilities in the spherical geometry of capsule implosions. Diagnosing such 3-D implosions remains a challenge. Los Alamos has led an experimental campaign of imploding cylinders using indirect drive in a hohlraum. This provides a convergent geometry but only in 2-D with good diagnostic access. Initial experiments proved that perturbations on the outer surface of the cylinder seeded ablative Rayleigh-Taylor instabilities that fed into a marker layer on the inside of the cylinder.[9] Inclusion of higher-opacity brominated plastic on the outside of the cylinder created increased hydrodynamic growth with growth factors of 10--20 for m=10 sinusoidal perturbations (Figure 4).[10] The experimental campaign is now exploring different mode amplitudes and wavelengths for comparison to hydrodynamic modeling. Future plans call for extending cylindrical implosions to direct drive on the OMEGA-Upgrade laser. Direct drive should increase the overall drive efficiency and hence allow both larger cylinders to be used and more energy in the implosions. This can improve the spatial resolution and allow studies of the coupling of hydrodynamics and thermodynamics of the implosions.

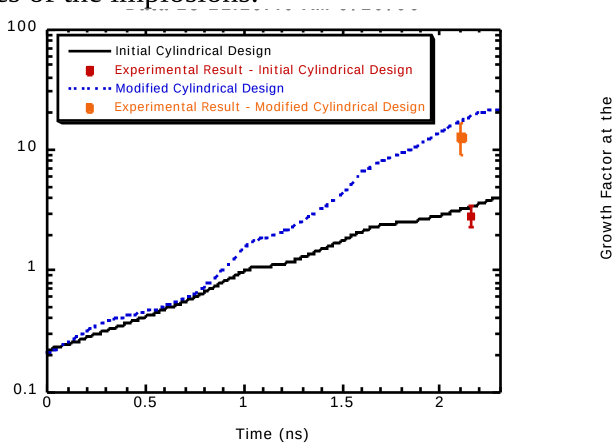


Figure 4: Calculated (using 1-D HYADES code) and measured growth factors for m=10 sinusoidal perturbations in a cylindrical implosion using pulse shape 22. The Modified Cylindrical Design uses brominated plastic to increase the growth factor.

B. Deuterated Shell Implosions and Direct Numerical Simulations

Los Alamos has developed the capability to perform direct numerical simulations (DNS) of multimode perturbation instability growth in two dimensions. These calculations have no adjustable model parameters for the "mix" that results from non-linear mode growth, and are directly coupled to burn calculations allowing determination of ignition margins from different perturbation amplitudes. These DNS calculations were used to analyze a series of spherical capsule implosions where the only fusion fuel was deuterium in the plastic of the capsule (made of CD_2 rather than CH_2), and the only route to fusion neutrons was mixing or spike penetration of the shell material into the hot compressed core.[11] The surface roughness of the CD_2 capsule was then varied by creating random pits on the surface by laser ablation. Using the DNS calculations rather than parametrized mix models provided agreement in the magnitude of the neutron emission as well as the reduction in yield as the surface roughness increased. As the surface roughness increased, the deuterium temperature increased but the deuterium density decreased as a result of perturbation growth.

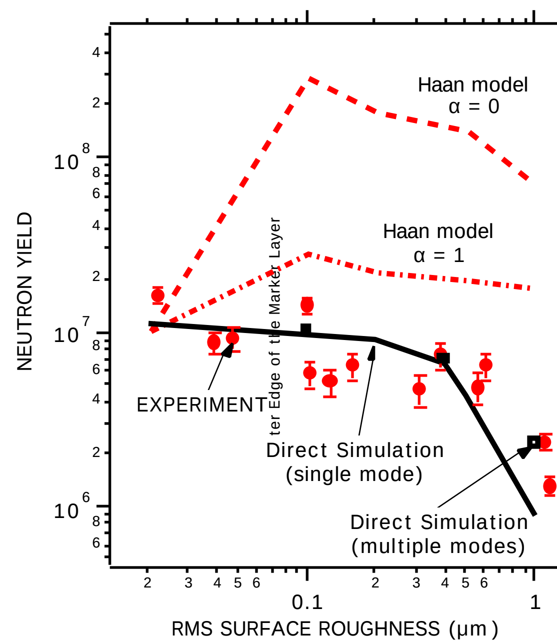


Figure 5: Neutron Yield (both calculated and measured) vs. RMS surface roughness of deuterated-plastic capsule implosions on Nova. The experimental data agrees both in magnitude and scaling with the Direct Numerical Simulations of instability growth.

C. Foam Buffering and Beam Smoothing

In collaboration with Imperial College (UK) we have conducted experiments on the Trident, VULCAN, Nova, and now OMEGA-Upgrade lasers investigating the use of low-density foam layers to mitigate direct-drive laser imprinting.[12] The foam quickly turns into a plasma (aided by a very thin high-Z coating) with high thermal conductivity. The result is that the location of the laser absorption layer and the position of ablation surface can be separated by some distance. Hot spots in the laser absorption can be smoothed or "buffered" by thermal conduction before they get to and imprint on the ablation surface and seed Rayleigh-Taylor instabilities. Present experiments must pay an energy penalty to vaporize the foam relative to deposited energy to drive implosions; however, on NIF the required energy to vaporize a foam layer to mitigate laser imprinting in the "foot" of the drive pulse is an insignificant fraction of the total energy of the pulse. Very successful mitigation of laser nonuniformities has been seen on experiments utilizing green (527 nm) lasers; experiments are just beginning to study the effect when using blue (351 nm) laser drive.

IV. TRIDENT LABORATORY

Several laser-matter interaction experiments discussed here as well as others from various national laboratories and universities have been performed at the Trident Laboratory at Los Alamos.[13] Trident has a three-beam frequency-doubled Nd:glass laser driver producing 0.1-2.0 ns pulses of 527 nm light containing 100-500 J per pulse (depending on pulselength). Resident experimental diagnostics include a variety of both time-resolved and time-integrated optical and x-ray instruments. This suite of diagnostics, along with a flexible and easily changed target illumination geometry and high shot rate (45 minute cool-down between shots) permits Trident to support a wide variety of ICF, SBSS, and other experiments and instrument development.

V. NIF TARGET DESIGN, TARGET FABRICATION TECHNOLOGY DEVELOPMENT, AND NEW INITIATIVES

Computational assessment of NIF ignition designs continues to be important to the ICF program. Ignition modeling is setting difficult but achievable requirements for target fabrication technology. Aspects of ignition designs using beryllium capsules are leading to new experimental initiatives.

A. NIF Target Designs

Los Alamos continues research to investigate the mainline NIF ignition targets (including both plastic and beryllium ablators) and the tolerances of NIF specifications as our modeling of target physics phenomena develops. We have extended NIF target design to include beryllium capsules and 3 rings of laser illumination on each end of the hohlraum for more symmetry control, and we are working on the design of non-cryogenic targets. Examples of calculations of the tolerance of NIF ignition to DT ice surface roughness are shown in Figure 6.

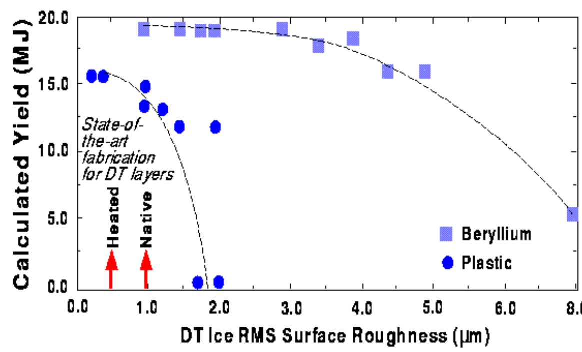


Figure 6: Calculated Yield vs. DT ice surface roughness for plastic and beryllium NIF target designs. The achieved state-of-the-art fabrication tolerances appear low enough to achieve ignition in both designs. The beryllium capsule tolerates greater DT ice surface roughness than the plastic capsule.

B. Target Fabrication Technology

The achievement of ignition will require significant materials science and technology research related to target fabrication. In particular, ignition targets will require special cryogenic developments that are being researched at Los Alamos and other laboratories. Using "beta-layering" techniques, Los Alamos has demonstrated cryogenic DT layers of unprecedented smoothness, with RMS surface roughness on the inside of the ice layer of 0.7–1.0 microns.[14]

While the low-Z of a beryllium pusher leads to an attractive ignition target, the low permeability of beryllium does not allow diffusion filling of Be capsules with DT. Be hemishells of 1–2 mm diameter have been successfully machined to the specifications for surface smoothness needed by NIF, better than 10–20 nm rms.[15] However, ignition targets must be fabricated and joined with joints or welds after filling, or a fill-tube of some sort must be implemented.

C. New Initiatives (Defects and Feedout)

The possible need to join hemispheres of beryllium after filling with DT gas has raised questions about the impact such "defects" in fabrication technology may have on implosion hydrodynamics and ignition. Study of such sharp features with small aspect-ratio (small size compared to capsule thickness) also pushes both experiment and theory in the study of development of non-linear hydrodynamics. Experiments are just beginning at Nova on the hydrodynamics of such defects.

"Feedout" is a mechanism by which perturbations on the inner DT ice surface can seed perturbations at the ablation surface which grow during the accelerating compression of the capsule. It is thought to be caused by a Richtmyer-Meshkov flow field that develops after a shock passes the perturbed surface. This entire flow field (the perturbed density, velocity, pressure, ...) propagates back to the ablation surface and seeds the ablative Rayleigh-Taylor growth there. This is thus different from the experiments where the ablative Rayleigh-Taylor growth is generated just by surface displacements. It is hypothesized that part of the resistance of the beryllium pusher to ice surface roughness (see Figure 6) may be from reduced feedout. Initial experiments at Nova have demonstrated the existence of the feed-out mechanism.

VI. WEAPONS PHYSICS ON LARGE LASERS

"A new approach to ensuring confidence in the U.S. stockpile is needed. This new approach must rely on scientific understanding and expert judgment, not on [underground] nuclear testing and the development of new weapons, to predict, identify, and correct problems affecting the safety and reliability of the stockpile."[16] Laser facilities can provide laboratories for high-energy-density physics where experiments can be performed as part of the development process for computer models used to enhance confidence in the stockpile. Laser facilities can also be used to perform experiments that generate high-quality and accurate data needed in those models. Los Alamos intends to participate in both types of experiments.

A. Equation of State

Accurate determination of the plutonium or DT equations of state are important experimental issues. Extremely accurate measurements of shock and particle velocity (1% uncertainty or better) are required to have significant impact on present theories and models. This requires diligent care to experimental details including fabrication tolerances and diagnostic measurements. Only modest laser energies are required to provide shock pressures of interest; however, extremely uniform laser illumination is desired to achieve excellent shock uniformity. Los Alamos is beginning experiments to make these detailed equation of state measurements.

VII. SUMMARY

To meet the principal goals of achieving ignition and support the stockpile, the Los Alamos ICF program has developed several program elements. Within each area we are conducting campaigns of focused research designed to address critical ignition issues and Stockpile Stewardship science.

ACKNOWLEDGMENTS

We have great appreciation for the technical staff at laser facilities such as Nova (LLNL), OMEGA (LLE-University of Rochester), and other institutions whose hard work and dedication provide the world-class facilities where we can collaborate in the science. This work supported under D.O.E. Contract W-7405-ENG-36.

REFERENCES

University of Nevada, Reno.
[†] Physics International, San Leandro, CA 94577

[1] A. A. Hauer et al., "The role of symmetry in indirect-drive laser fusion," *Phys. Plasmas* **2** (1995) 2488.

[2] N. D. Delamater et al., "Symmetry experiments in gas filled hohlraums at Nova," *Phys. Plasmas* **3** (1996) 2002.

[3] H. A. Rose, "Laser beam deflection by flow and nonlinear self focusing," *Phys. Plasmas* **3** (1996) 1709.

[4] J. C. Fernández et al., "Dependence of Stimulated Brillouin Scattering on Laser Intensity, Laser F Number and Ion Species in Hohlraum Plasmas," *Phys. Rev. E* **53** (1996) 2747.

[5] R. G. Watt, J. Cobble, R. P. Drake, Bruno S. Bauer, D. F. DuBois, J. C. Fernandez, and Harvey A. Rose, "Dependence of stimulated Brillouin scattering on focusing optic F number in long scale length plasmas," *Phys. Plasmas* **3** (1996) 1091.

[6] H. A. Rose et al., *Phys. Rev. Letters* **72** (1994) 2883.

[7] J. C. Fernández et al., "Observed Dependence of Stimulated Raman Scattering on Ion Acoustic Damping in Hohlraum Plasmas," (submitted to *Phys. Rev. Letters*, 1996).

[8] B. A. Remington et al., "Laser-driven hydrodynamic instability experiments," *Phys. Fluids B* **5** (1993) 2589. B. A. Remington et al., "Single-mode and multimode Rayleigh-Taylor experiments on Nova," *Phys. Plasmas* **2** (1995) 241.

[9] W. W. Hsing and N. M., Hoffman, "Measurement of feedthrough of the Rayleigh-Taylor instability in cylindrical implosions," (submitted to *Phys. Rev. Letters*, 1996).

[10] J. B. Beck, "The Effects of Convergent Geometry on the Ablative Rayleigh-Taylor Instability in Cylindrical Implosions," Ph.D. Thesis, Purdue University, May, 1996.

[11] O. L. Landen et al., "High-Growth-Factor Implosions (HEP4)," in *1995 ICF Annual Report*, UCRL-LR-105820-95, Lawrence Livermore National Laboratory.

[12] M. Dunne, M. Borghesi, A. Iwase, M. W. Jones, R. Taylor, O. Willi, R. Gibson, S. R. Goldman, J. Mack, and R. G. Watt., "Evaluation of a Foam Buffer Target Design for Spatially Uniform Ablation of Laser-Irradiated Plasmas," *Phys. Rev. Letters* **75** (1995) 3858.

[13] N. K. Moncur, R. P. Johnson, R. G. Watt, and R. B. Gibson, "Trident: a versatile high-power Nd:glass laser facility for inertial confinement fusion experiments," Appl. Opt. **34:**21 (1995) 4274.

[14] see J. L. Hoffer et al., "Surface Roughness Measurements of Beta-Layered Solid Deuterium-Tritium In Toroidal Geometries," this conference, paper #04.04.

[15] see P. L. Gobby et al., "Current Progess in NIF Target Concepts," this conference, paper #04.06.

[16] "The Stockpile Stewardship and Management Program: Maintaining Confidence in the Safety and Reliability of the Enduring U.S. Nuclear Weapon Stockpile," U.S. Department of Energy , Office of Defense Programs, May 1995.